4. The Variability–Evolution Connection

OBSERVATIONS OF LONG PERIOD VARIABLE STARS

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1. INTRODUCTION.

The study of long period variable stars has been transformed in recent years by two observational developments. Large samples of stars have been observed at infrared wavelengths, providing knowledge of the intrinsic properties of the star as well as of circumstellar dust shells, and these observations have been extended to the variables in well defined stellar systems to allow their properties to be studied in relation to the stellar population to which they belong. Spectroscopic determinations of chemical composition have also provided several crucial insights.

2. TYPES OF OPTICALLY SELECTED RED VARIABLES

The fourth edition of the General Catalogue of Variable Stars (Kholopov et al. 1985) lists over 11,000 red variables. Several hundred, most of them M giants, have published spectral types or infrared photometry. The stars are classified on the basis of light curves in the photographic or visual regions as irregular (L), semiregular (SR) or Mira Ceti type (M). The distinction between SR and M is primarily one of amplitude: the frequency of amplitudes of red variables has a minimum at 2.5 mag in blue or yellow light and the Miras have larger amplitudes (Payne-Gaposchkin 1951). The Miras of spectral class M or S usually have much larger amplitudes, typically 5-8 magnitudes, because TiO and other bands which strengthen towards minimum light absorb preferentially in B and V (e.g. Smak 1966). The amplitudes in J (1.2 μ), K (2.2 μ) and in m_{bol} are only in the ranges 0.3-1.4 mag, 0.2-1.0 mag and 0.3-1.2 mag, respectively (Feast et al. 1982). The carbon variables usually have quite small amplitudes in V, with more rounded light curves (Alksne et al. 1981; Wing 1985). The blue amplitude of a variable carbon star might be enhanced relative to the amplitude in V by variation of the violet opacity. The classification of the carbon stars is correspondingly less certain than for M stars.

The SR variables are divided into SRa stars which have persistent periodicity although with variable amplitude and light curve shapes and SRb stars which have less marked periodicity which may be interrupted by intervals of irregularity or even constancy. An important subgroup of the SRb stars comprises those which show two periods simultaneously, so that the mean magnitude may change in a much longer period than the normal variation. Houk (1963) lists over 100 such stars, including 66 of spectral class M and 20 of class N. The ratio of the two periods,

P_2/P_1, is approximately 9.4 for M stars and 12.2 for N stars; there are some very discrepant values (Payne-Gaposchkin 1954; Houk 1963).

The Mira variables show H emission during part of the light cycle. Those semiregular variables with weak emission lines belong to a population of higher velocity and presumably greater age than the stars without emission (Feast et al. 1972). Hydrogen emission in stars of relatively small amplitude is also found among the SRd variables of Population II (Rosino 1951, Feast 1965) and in some variables in globular clusters (Joy 1949, Lloyd Evans 1983a).

The classes described here refer specifically to giant stars. M supergiants, which are often found in associations or young clusters and are believed to have $m \gtrsim 9m_{\odot}$, are classed as SRc or Lc; there are no Miras.

3 POPULATIONS OF RED VARIABLES

3.1 Galactic Globular Clusters

The richest clusters contain sufficient stars to show how the variability of a star develops as it ascends the giant branch. Optical studies especially of 47 Tuc (Arp et al. 1963; Eggen 1972; Lloyd Evans & Menzies 1973; Lloyd Evans 1974, 1983b; Fox 1982), show that a star varies with increasing amplitude and lengthening period until it becomes a Mira variable (Feast 1973). There are also variables of small or moderate amplitude which lie above, or perhaps more accurately to the blue of, the giant branch. These are still quite close to the tip of the giant branch and are not to be confused with the Type II Cepheids and RV Tauri stars which lie in the Cepheid instability strip. They have been referred to as Pec (Frogel 1983) or supra-giant branch (SGB) (Lloyd Evans 1983a). Infrared JHK photometry of 47 Tuc (Frogel et al. 1981) confirmed the picture obtained from VI photometry and in addition showed that the luminosity of the three Mira variables as well as the semiregular V4 placed them above the tip of the first giant branch and so presumably on the asymptotic giant branch (AGB). Infrared studies of several clusters (Frogel 1983; Frogel & Elias 1988) show that this is generally true of Mira variables (which they denote LPV), while the fainter irregular and semiregular variables could equally well be on their first ascent of the giant branch. The Miras have infrared excesses at 3.4μm and 10μm as well as enhanced H_2O absorption; this may indicate mass loss. These properties are also exhibited, less markedly, by the stars which fall to the blue of the giant branch. The latter generally have luminosities close to that of the top of the first giant branch.

Galactic globular clusters cover a wide range of metal content while all are of a similar great age (e.g. Buonanno 1986, Burstein 1985) so that intercomparing the variables in these clusters shows the effect of varying metal content in stars of a similar low mass. The most metal deficient clusters contain red variables with small amplitudes and short periods; they are not confined to the immediate tip of the giant branch (Eggen 1972). Variability of small amplitude sets in at redder V-I colour and hence later spectral type the higher the metal content in the more metal rich clusters (Lloyd Evans & Menzies 1973, 1977; Lloyd Evans 1983b). The periods of the Mira variables are longer the more metal-rich the cluster (Lloyd Evans & Menzies 1973; Lloyd Evans 1983a). There is no case known of Mira variables of significantly different period belonging to the same cluster. Frogel & Elias (1988) find that the more metal-poor clusters with [Fe/H] $\lesssim$ -1.0 have no stars with the infrared excesses, H_2O absorption and high luminosity of Miras, although the variables displaced to the blue of the giant branch are found over the whole range of [Fe/H], - 2.0 to -0.3. The two cluster Miras of shortest period, V42 (P = 149 d) in ω Cen which has a spread of metal abundance, and V16 (P = 135 d) in NGC 362 which has [Fe/H] = -1.3, were not observed because of crowding, however.

Frogel et al. (1981, 1983) found from observations of a large sample of globular cluster giants that the large amplitude variables (Miras) are displaced from the locus defined by the other stars in the J-H, H-K diagram. This displacement is closely correlated with the strength of the H_2O band at 1.9μm.

Menzies & Whitelock (1985) obtained JHKL photometry for twelve Miras in galactic globular clusters and derived a period-lumiunosity relation, subject to some uncertainty arising from the determination of the relative distances of the clusters.

The globular cluster variables are generally of type K or M, depending on temperature and metal content (Feast 1973). Marginal S stars have been reported in NGC 6723 but were not found in 47 Tuc (Lloyd Evans 1984). Clusters which are much more metal deficient than NGC 6723 contain no stars with molecular bands such as TiO in any case. ω Cen contains several S stars of rather low luminosity which probably owe their enhanced ZrO to the unusual primordial chemical composition of the cluster rather than to the appearance of the products of reactions within these stars (Lloyd Evans 1983c). These would be "spectroscopic S stars" as defined by Little et al. (1987). Observations of Tc and binarity studies would be valuable. Three of the stars are variable; V6 belongs to the class of semiregular variables which resemble Miras in having strong H emission (Dickens et al. 1972) and lies at or just above the luminosity of the tip of the first giant branch (Frogel 1983). Although no S type Mira is known in a globular cluster, the example of the field Se variable NT Tel (P = 252 days) which has a very high radial velocity (Catchpole & Feast 1971; Andrews 1975) suggests that such stars might be looked for in clusters.

3.2 The Solar Neighbourhood

The solar neighbourhood contains a large number of Mira variables bright enough for detailed study, although individual distances and relative luminosities are usually not obtainable.

The classical division of the red variables into irregular, semiregular and Mira types may be tested against infrared photometry.

Fig 1

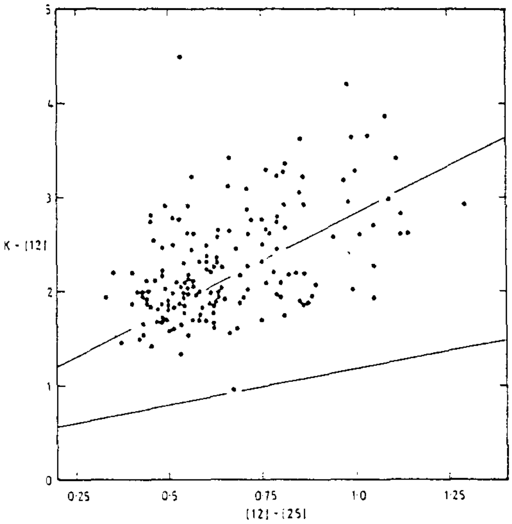

Fig 2

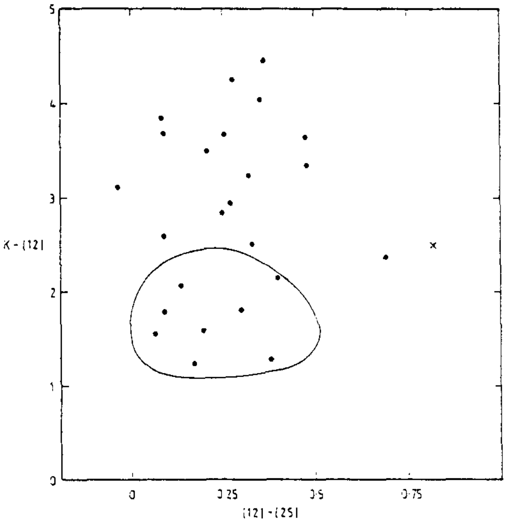

Fig 1. M-type Miras. The L and SR stars fall between the two straight lines.

Fig 2. Carbon Miras. The L and SR stars lie in the region indicated, with a few exceptions such as R Scl (cross).

Figs 1 and 2 show the K-[12] against [12]-[25] for M and N stars, respectively, combining 2µm photometry by Neugebauer & Leighton (1969) and Catchpole et al. (1979) with 12µm and 25µm photometry from the IRAS Point Source Catalogue (Beichman et al. 1985). The Miras are plotted individually while almost all other variables, except for a few SRa stars most of which have H emission, fall in the regions indicated. There is no such distinction between the other types of red variable. This is consistent with the conclusions of Frogel & Elias (1988) for globular cluster stars.

The Mira variables of type M are well separated from the small amplitude variables in the J-H, H-K diagram (Feast et al. 1982), reflecting the occurrence of strong H_2O absorption in the H band in the Mira variables but not in the constant M stars or those with small amplitudes of variation (Hyland 1974, Frogel et al. 1981). Miras which are known to have OH or H_2O masers are displaced by more than the average amount in this diagram, and are also displaced towards larger J-K and K-L in the J-K, K-L diagram. The Se variables do not show such displacements as a group, nor do they exhibit H_2O absorption bands or OH or H_2O maser emission (Hyland 1974). However the Se stars are displaced from the S stars as a group, more nearly parallel than perpendicular to the black body line. The carbon Miras are less well separated from variables of small amplitude, except for a few very red stars. Catchpole & Feast (1985) show that the latter include V Hya, a spectacular example of the doubly periodic stars (Houk 1963; Mayall 1965).

Kinematic studies of the Mira variables (Feast 1963) showed that the longer period stars have lower velocities relative to the Sun, suggesting that period depends on age and mass. M-type Mira variables with P $\lesssim$ 200 days have a large systematic motion with respect to the local standard of rest which associates them with Population II, consistent with the presence of Miras with P ~200 days in metal-rich globular clusters. Stars with P > 400 days have a small systematic motion and they were identified with a Hyades population, corresponding to an age of ~5×10^8 years and a mass of 2.5 m_0 on the main sequence.

Robertson & Feast (1981) analysed the infrared data of Catchpole et al. (1979) to find M_{bol} ~ -3.9 for the whole period range 150-600 days from statistical parallaxes, whereas the stars in clusters and binaries showed a trend from -3.8 at 200 days to -4.9 at 350 days. The Type II OH/IR sources fall on an extension of the period-luminosity relation, drawn primarily from Miras in the LMC (Feast 1984), to periods in the range 600-1800 days (Engels et al. 1983; Feast 1985). The masses must be quite small (Feast 1986).

The S and carbon Miras are few in number and do not lend themselves to statistical analysis. Their periods are much longer than those of the M stars in the mean; Merrill's (1960) study shows that the S stars are common only for P > 280 days while most N stars have P > 350 days. Analogy with the Magellanic Cloud data (Section 3.4) suggests correspondingly higher bolometric luminosities and perhaps masses than for the shorter period Miras of spectral type M.

Lloyd Evans (1985a) noted that the proportion of Miras among the red stars is at a maximum for the extreme S, SC and weak-banded carbon types. This was attributed to these stars being formed by the envelope-burning process at high luminosity but the situation may be more apparent than real. Factors contributing to this are: (1) the bias towards cool stars of the main search technique for pure S stars (Keenan 1954) results in a bias towards the discovery of Mira variables (Lloyd Evans & Catchpole 1988), (2) hot SC stars are difficult to find, because of the weakness of the molecular bands, and are not obviously distinguishable from the Ba stars which are probably not AGB objects (Yorka & Keenan 1985), (3) Tsuji's (1981a, b) temperature calibration for small amplitude variables among the N stars shows that the C_2 bands increase in strength as the effective temperature decreases from 3200 to 2400 K; the Mira variables must be cooler than this and are probably beyond the peak in the C_2-T relation (Morris & Wyller 1967) so that the weakness of the C_2 bands may be a temperature effect.

3.3 The Galactic Centre

The red variables in the central bulge of the Galaxy have been observed via the Baade windows in the foreground dust clouds. Visible light studies revealed 113 Mira variables (Lloyd Evans 1976); a few additional stars, with periods in excess of 400 days, were discovered on the original plates at the position of IRAS sources but the search appears to have been complete for shorter period stars (Feast 1986; Glass 1986). The very long period stars are only observable in visible light for a short period around maximum light and are not identifiable as Miras on the basis of amplitude.

Some of the Miras with $P \gtrsim 400$ d have exceptionally red colours (Glass & Feast 1982; Wood & Bessell 1983; Glass 1986). Whitelock et al. (1986) have interpreted these as stars with very thick circumstellar shells, similar to WX Ser, IK Tau and WX Psc in the solar neighbourhood. These extreme Miras, which have very long periods, are considered as intermediate between typical optically-selected Miras and the Type II OH/IR variables which can only be studied at longer wavelengths.

Lloyd Evans (1976) considered two extreme possibilities for the galactic centre Miras: the period-age relationship for field stars (Feast 1963) suggested that the long period Miras might be of age similar to the Hyades, while extrapolation of the period - [Fe/H] relationship for those in globular clusters (Lloyd Evans & Menzies 1973) implied that they are metal rich but possibly very old. The mounting evidence for a very metal-rich component in the central bulge of the Galaxy (e.g. Whitford & Rich 1983) and the lack of evidence for the many main sequence A stars implied by the first possibility suggested that the second case is more nearly correct. Wood & Bessell (1983) argued for much higher masses and a correspondingly young age for the bulge Miras, but their arguments have been disputed by Feast (1986) and Frogel & Whitford (1987). The latter present evidence that these Miras are not different from those found elsewhere and that they have masses and ages similar to globular cluster stars.

There appear to be no carbon stars among the Miras, nor are any N stars known in the galactic centre fields (Lloyd Evans 1976; Blanco et al. 1984). This is an important difference between the variable star population in the central bulge of the Galaxy and that in the vicinity of the Sun.

The period-luminosity relation for Mira variables in the galactic bulge has been studied on the basis of JHK photometry (Glass & Feast 1982, Wood & Bessell 1983, Feast 1986). The slope is not significantly different from that in other samples and the zero point is the same as in galactic globular clusters and the Magellanic Clouds if the same assumptions are made about the luminosity of the RR Lyrae stars in each system (Feast & Whitelock 1987).

3.4 The Magellanic Clouds

The Magellanic Clouds are of particular importance because they contain a wide range of stars of different age and composition at the same distance, so that relative luminosities can be obtained and evolutionary conclusions drawn. There are two types of large amplitude variables. The Shapley-Nail variables are bright visually and were discovered by the Harvard observers (Shapley & Nail 1951, Payne-Gaposchkin & Gaposchkin 1966, Payne-Gaposchkin 1971). They have a period-visual luminosity relation in the opposite sense to that of galactic Miras (Buscombe et al. 1954), visual amplitudes $\Delta V \gtrsim 5$ mag and strong H emission lines (Lloyd Evans 1971a). They are believed to be massive AGB stars, $m \lesssim 7\ m_{\odot}$, on the basis of surface distribution (Lloyd Evans 1971a, 1985a) as well as comparison with lines of constant pulsation mass in the M_{bol}, P diagram (Wood et al. 1983; Wood et al. 1985). The frequent occurrence of ZrO indicating s-process enhancement and probably a raised C/O ratio in the envelope also suggests they are AGB stars (Wood et al. 1983).

Stars comparable to galactic Mira variables have been found by using V and I plates taken with larger telescopes (Lloyd Evans 1971b; Glass & Lloyd Evans 1981; Wood et al. 1985; Glass & Reid 1985; Glass et al. 1987; Lloyd Evans et al. 1988; Reid et al. 1988). These stars fall on a P - M_{bol} locus which is similar to and perhaps identical with that seen in the solar neighbourhood (Robertson & Feast 1981) and globular clusters (Menzies & Whitelock 1985; Feast 1986). The high luminosity stars fall on a steeper locus which may intersect that of the ordinary Miras near P = 250 days; however most of the stars are clumped between M_{bol} = -5.8 and -6.8 with only a few to define the lower part of the locus (Wood et al. 1983; Lloyd Evans 1985a; Lloyd Evans et al. 1988; Reid et al. 1988). The two CS stars (Lloyd Evans 1980, 1985a) may both belong to the ordinary Mira population (Lloyd Evans et al. 1988). The stars of high luminosity are estimated to be ~10^8 years old and their separation from the much older ordinary Miras may result from episodic star formation in the Magellanic Clouds which has resulted in partial filling of a broad instability region in the period-luminosity plane (Wood et al. 1983; Wood et al. 1985; Reid et al. 1988).

The M, S and C stars follow an almost identical locus in the P, K diagram but the carbon stars are fainter at given period in the P, M_{bol} diagram. The difference is much smaller than would be expected from current understanding of the T_{eff}, J-K relation for cool stars (Wood et al. 1985) but the bolometric luminosity may not be accounted for satisfactorily by observations extending only to 2.2 μ (Glass et al. 1987).

The inventory of the ordinary Miras may be incomplete for the visually fainter long period stars of M and S type especially. The periods of some of the stars are poorly known and there may be a few SR variables in the current lists. Glass et al. (1987) find for the LMC a total of 32 probable M stars, 3 S stars and 37 carbon stars. The more fragmentary data for the SMC comprises one M star, plus two of short period which may not be Miras (Lloyd Evans 1985a), five C stars and the two CS stars referred to above (Lloyd Evans et al. 1988). The SMC lacks the 200-day Miras which are common in the other systems, perhaps because the heavy element content was too low to produce this 47 Tuc component some 14 x 10^9 years ago. The mean periods of the carbon Miras in the various systems are: SMC, 310 days (Lloyd Evans et al. 1988; LMC, 320 days (Wood et al. 1985; Reid et al. 1988); solar neighbourhood, 400 days (Kholopov 1985); galactic central bulge, none found (Lloyd Evans 1976). This matches the relative metal contents of these stellar systems.

The intrinsic colours of the high luminosity stars show the same shift from the intrinsic line towards the blackbody line in the J-H, H-K diagram as galactic Miras, with some detailed differences attributable to peculiarities in composition (Elias et al. 1985; Lloyd Evans 1985a). The absence of galactic counterparts of these stars, which are especially common in the SMC, has been attributed to the development of obscuring dust shells around the more metal rich galactic stars (Lloyd Evans 1971a; Elias et al. 1985). The relatively low luminosity of the OH/IR stars, which lie on a linear extension of the P-L relation for the Mira variables (Engels et al. 1983; Feast 1985) and are therefore nearly a magnitude fainter than the bright Magellanic Cloud stars at P ~600 days, may rule them out of consideration as possible counterparts. Their masses, ~ 1.3 $m_\odot$ (Feast 1986), are much less than those considered likely for the bright Magellanic Cloud stars (Lloyd Evans 1971a; Wood et al. 1983; Lloyd Evans 1985a). The indirect (kinematic) nature of the luminosity estimates for OH/IR stars may leave room for an unrecognised population of more luminous OH/IR stars in the Galaxy. The Magellanic Cloud stars are mostly of spectral type MS (Wood et al. 1983), with C/O ~1. Thus most of the O may be taken up in the CO molecule leading to a weakness of OH emission in dusty galactic counterparts which would otherwise appear as OH/IR stars.

4 CIRCUMSTELLAR DUST SHELLS

The early ground-based infrared studies showed that Mira variables, as well as M supergiants which are generally variables of small amplitude, have large infrared excesses and 10μm emission bands which are different in carbon and oxygen stars (Woolf & Ney 1969; Gehrz & Woolf 1971; Dyck et al. 1971).

The development of circumstellar shells from the optically thin shells of typical Miras to the increasingly thick dust shells of OH/IRC, OH/AFGL and OH/IR stars was traced by ground based work (e.g. Engels et al. 1983) and has been studied in more detail using IRAS photometry (Olnon et al. 1984; Bedijn 1987; van der Veen & Habing 1988). The reddest and coolest shells of all belong to non-variable OH/IR stars and are considered the last stage in the evolution of an AGB star before the development of a planetary nebula. The variable objects lie on a smooth track in the [12]-[25], [25]-[60] diagram, which can be interpreted in terms of a single dust shell of increasing optical thickness whose inner radius lies at the point where dust condensation occurs in the case of the variable objects. Mass loss occurs at an increasing rate along the track (Rowan-Robinson et al. 1986; Bedijn 1987), matching the increasing amplitude of the driving pulsation of the central star, from $\Delta K \sim 1$ mag for a typical Mira (Feast et al. 1982) to 4 mag for some of the OH/IR stars (Engels et al. 1983). The [25]-[60] colours of the irregular, semiregular and optical Mira variables lie in the range -0.4 to +0.2 and as yet show no increase with increasing [12]-[25].

Van der Veen & Habing (1988) give the [12]-[25], [25]-[60] diagram for all reliable Point Source Catalogue data and find a gap in the distribution of [12]-[25] values, from 0.15 to 0.45 (applying the zero point corrections, which they omit, to match our Fig 1). These correspond to the Rayleigh-Jeans point for a cool photosphere and the blue edge of the Mira zone, respectively. The gap is populated by some of the small amplitude variables whose colours range from the Rayleigh-Jeans point to [12]-[25] ~ 1.1 which is also the limit for optically selected Miras. The globular cluster data show that the small amplitude variables are more numerous than the Miras which they precede in evolution (Feast 1973) and the prominence of the gap must arise from a combination of the contribution of more common stars of a range of temperature to the Rayleigh-Jeans sources coupled with the much greater luminosity at 60 μm, the selection flux, of the Mira variables compared to the irregular variables. The density of points along the track does not correspond to the rate of evolution, as the evolution is probably not monotonic towards redder [12]-[25] in the early stages and flux selection plays a vital role.

De Gioia-Eastwood et al. (1981) have shown that the rate of mass loss increases monotonically with the period of an optical Mira, while Whitelock et al. (1987) show that it is also related to the amplitude of pulsation at a given period. The outflow velocity measured in the 1612 MHz line of OH emission in circumstellar envelopes increases with the period (Dickinson et al. 1978). Vardya et al. (1986) find that the infrared spectra (IRAS Science Team 1986) and hence the dust properties depend on the shape of the light curve which in turn may be an indicator of the strength of the atmospheric shock wave. An asymmetric light curve tends to be associated with stronger 9.7μm silicate emission.

Lloyd Evans (1987) found that the [12]-[25] and to a lesser extent K-[12] colours were redder for the doubly periodic stars than for singly periodic SRb stars of similar amplitude. They have the strongest 10 μm silicate emission of any of the red giant variables. This parallels the enhanced infrared excess in RV Tauri stars which show a long wave as well as the usual short period variation (Lloyd Evans 1985b). The RV Tauri stars lie far to the blue of the giant branch, in and to the red of the Cepheid instability strip. This tempts the speculation, in the absence of direct evidence, that there is a connection between the doubly periodic variables and those globular cluster variables which fall to the blue of the giant branch and have enhanced infrared emission and H_2O absorption relative to ordinary irregular and semiregular variables (Frogel & Elias 1988). The physical reason for the slow secondary variation is unknown (Wood 1975).

Similar properties are found for the S, SC and N stars, although with some differences in detail. The Miras have enhanced K-[12], considered as a group (Fig 2); the relatively small values of some of the carbon stars may indicate difficulties in classification arising from the smaller amplitudes and the red B-V of carbon variables. Jura (1986) and Claussen et al. (1987) used the IRAS data to show that mass loss increases with period and amplitude among C stars and Jura (1988) obtained the same result for S stars. These studies do not distinguish between Miras and SR variables, except by way of the 2μm variation (Neugebauer & Leighton 1969), so a large part of the period dependence results from comparing Miras with semiregular variables which generally have shorter periods.

Feast et al. (1984) reported that R For (a carbon Mira of P = 388 d) became unusually faint in both visible and infrared radiation during 1983; this was attributed to a change in circumstellar obscuration. Le Bertre (1988) was able to explain this with a model in which the dust grains in the inner part of the circumstellar shell are alternatively formed and destroyed as the central star fades and brightens. The 1983 event resulted from an unusually faint minimum of the central star.

The distribution of the S stars in [12]-[25] is similar to that of the M stars but carbon stars are largely confined to the range 0.0 to 0.5 (Fig 2). Willems (1986) finds that the carbon SR and Lb variables are more scattered than the Miras in the [25]-[60], [12]-[25] diagram: he attributes this to episodic mass ejection in the variables of small amplitude while the Miras undergo steady mass loss leading to more uniform shells. R Scl (SRa, P = 370 d) is a case in point: Rowan-Robinson et al. (1986) deduce from the IRAS photometry that ejection of a shell ended about 100 years ago, leaving a cool distant shell today, or even that we see a primordial dust shell; even at 12μm the dust emission is unusually strong for a SR variable (Fig 2).

Secondary periods are at least as common among N stars as among the M stars (Houk 1963). V Hya, with periods of 530 and 6500 days, is one of the most spectacular stars of this type and has even been misclassified as a Mira because of the large total amplitude, ΔV ~ 6 mag. Mayall (1965) gives a light curve. Forrest et al. (1975) discovered the large infrared excess. Spatial variations in the 2.6 mm CO emission reveal a bipolar outflow in the outer envelope which extends to at least 20 arcsec from the star (Tsuji et al. 1988; Kahane et al. 1988) and this may be related to the unusually rapid rotation of this star.

Knapp & Morris (1985) have deduced from CO observations of the envelopes of a large sample of long period variables that they lose mass at rates of 3×10^{-8} to 2×10^{-4} $M_{\odot}$ yr^{-1}. The higher rates are for stars with optically thick envelopes, several of which are optically bright C or S stars including R Scl (SRa, P = 370 d) and the doubly periodic V Hya as well as Mira variables.

5 ABUNDANCE INDICATORS OF EVOLUTION

The occurrence of S and N stars among the longer period Miras (Section 3.2, 3.4) indicates that the third dredge-up (Iben & Renzini 1983) occurs in them. Little et al. (1987) find that the radioactive ^{99}Tc (half-life = 2 x 10^5 years) occurs in most M type Miras with P > 300 days, indicating that the third dredge-up has begun even though C/O < 1. ^{99}Tc is also seen in almost all S and carbon Miras, but not in M stars which are constant or variable with a small amplitude. ^{12}C/^{13}C increases along the sequence M with no Tc, M with Tc, MS, S, indicating the dredge-up of increasing quantities of triple-alpha helium. Some MS and S stars which are small-amplitude variables show no Tc and may be cool Ba stars (Little et al. 1987). Dominy & Wallerstein (1986) have shown how quantitative abundances of several elements may be used to deduce details of the s-process events in Mira variables.

6 ATMOSPHERIC STRUCTURE

Mira variables show a spectacular range of emission features, both of lines and bands, as well as doubling of absorption lines (Merrill 1960). Observational work in recent years has concentrated on studying the kinematic structure of the deep atmosphere of M and S stars. This is best done at wavelengths of 2μm because of the lower Rayleigh scattering opacity (Willson et al. 1982; Hinkle et al. 1984). Additional absorption by TiO bands obscures other features in the near infrared so that line doubling can be seen in this region in S stars (Merrill & Greenstein 1958) but only in a few M stars which have weak TiO near maximum light (Willson et al. 1982.

The picture revealed by studies of absorption lines in the visible (Willson et al. 1982; Wallerstein 1985) and infrared regions (Hinkle, et al. 1982; Hinkle et al. 1984) and of emission lines (Fox et al. 1984; Gillet 1988) is of several distinct levels. Circumstellar gas in a slowly expanding shell at a temperature of not more than 300 K is revealed by resonance lines. The SiO maser emission may arise in a hotter layer below this and above the photosphere, so-called although it has a low velocity of infall, which is indicated by the absorption lines of excited levels in the blue spectral region; it shows little change of velocity with phase. Stellar oscillation drives a shock which passes through the stellar atmosphere near maximum light. The infrared absorption lines are double near maximum light, from which phase a continuous velocity curve can be traced, from about -15 km s^{-1} to +15 km s^{-1} (in χ Cyg, see Hinkle et al. 1982) at the next light maximum when the curve reverses shortly before that component disappears. Ionization occurs immediately below the shock and Balmer emission lines of H are produced by recombination below this; their profiles are distorted by atomic and molecular absorption in the cooler overlying layers. Some of the structure in the emission lines may result from the visibility of both advancing and receding parts of the shock zone near the limb (Gillet 1988). Emission lines of Mg I and Si I arise from thermal excitation (Fox et al. 1984), whereas the selective excitation of certain lines of Fe I is attributed to optical pumping by strong Mg II emission (Thackeray 1937).

Emission bands of AlO have been seen at a faint maximum of o Ceti (Merrill 1940) while Herbig (1956) identified many emission lines seen at minimum light in several stars as arising from AlH. The normal band structure is lost in this case because the AlH molecules are formed directly in the A'Π state by inverse predissociation and only short sequences of rotational levels are populated.

The less-studied carbon stars show the same characteristic emission lines of metals and hydrogen (Merrill 1960), although the relative intensities are different because of the different overlying absorption. A new feature is the appearance of C_2 emission at 4737Å and 4715Å (Lloyd Evans, to be published). This has been seen on the rising branch of the light curve in R Lep (Mira) but also appears in R Scl (SRa) and V Hya (doubly periodic SR) and other stars. The principal common factors are a very red colour or very strong SiC_2 absorption bands. The absence of the emission bands at minimum light in R Lep argues against one possible explanation, that they are circumstellar or chromospheric features seen against a weak continuum.

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